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EXTENDED TUNABILITY IN A TWO-CHIP VECSEL (POSTPRINT)

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Aerospace Components and Subsystems Technology Division

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14. ABSTRACT
We demonstrate a widely tunable vertical-external cavity surface-emitting laser (VECSEL) with a W-shaped cavity, in which two VECSEL chips serve as fold mirrors and a birefringent filter is inserted at Brewster's angle. These two chips provide much higher modal gain and broader bandwidth of the gain than a single chip does, enhancing the VECSEL tuning range and reducing the variation of tunable output power with the tuned wavelength. This two-chip VECSEL configuration makes it possible to shape the modal gain spectra of the laser or to manipulate the tuning curve of the laser by two different chips with certain gain peak detuning (offset). Multiwatts high-brightness linearly polarized output with a tuning range of 33 nm is demonstrated in such a two-chip VECSEL.

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Extended Tunability in a Two-Chip VECSEL

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***Abstract*—We demonstrate a widely tunable vertical-external-cavity surface-emitting laser (VECSEL) with a W-shaped cavity, in which two VECSEL chips serve as fold mirrors and a birefringent filter is inserted at Brewster's angle. These two chips provide much higher modal gain and broader bandwidth of the gain than a single chip does, enhancing the VECSEL tuning range and reducing the variation of tunable output power with the tuned wavelength. This two-chip VECSEL configuration makes it possible to shape the modal gain spectra of the laser or to manipulate the tuning curve of the laser by two different chips with certain gain peak detuning (offset). Multiwatts high-brightness linearly polarized output with a tuning range of 33 nm is demonstrated in such a two-chip VECSEL.**

***Index Terms*—Birefringent filter (BF), optically pumped semiconductor laser, tunable linearly polarized vertical-external-cavity surface-emitting laser (VECSEL).**

HIGH-POWER high-brightness tunable vertical-external-cavity surface-emitting lasers (VECSELs) are attractive for a wide range of applications [1]–[4]. Since VECSELs are low-gain lasers, the key to the high output power with a large tunability is to achieve higher and broader modal gain spectra and lower the loss of the wavelength selective component at the tuned wavelength. Based on this idea, the tunable VECSEL, using a birefringent filter (BF) and a cavity folded at the VECSEL chip, was successfully developed, and multiwatts high-brightness linearly polarized output power with a tuning range of 20 nm was demonstrated [1]. Also the tunable blue–green VECSEL was achieved by combining this tunable infrared VECSEL with intracavity second-harmonic generation [4].

Recently we proposed the multichip VECSEL as an efficient coherent power scaling scheme [5]. In this laser, the waste heat is distributed on each chip such that more pump power can be launched into VECSEL chips before the laser reaches its thermal rollover. When the modal gain peak of each chip was tuned to overlap each other, a two-chip VECSEL employing two slightly different VECSEL chips gave the best performance with over 19-W output power, which almost doubled the maximum output power of a single-chip VECSEL. Since the modal gain spectra of the multichip VECSEL are the superposition of the gain spectra of each chip, a multichip VECSEL achieves a higher gain and a broader gain bandwidth than a single-chip VECSEL does, resulting in the potential of a larger tunability with high output power. In addition, the quantum-well gain spectrum is sensitive to its structure, carrier density, and temperature. A multichip configuration yields a flexibility to control its modal gain spectra by changing the pump or temperature on each chip, manipulating the tuning curve (output power versus tuned wavelength) of the laser such that the laser provides a larger tuning range and less variation of output power with the tuned wavelength. Also, a multichip passively mode-locked VECSEL has the potential to overcome the average power limitation, and its extended bandwidth of gain is of great importance for the generation of ultrashort pulses [6].

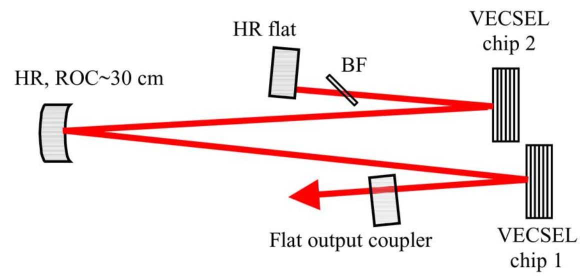

Fig. 1. Schematic diagram of a tunable two-chip VECSEL with a W-shaped cavity and a BF. Relative dimensions not to scale.

In this letter, we present the development of a tunable two-chip VECSEL with a W-shaped cavity and a BF, and investigate how a two-chip VECSEL will improve its tunability and output power variation with the tuned wavelength. Multiwatts high-brightness linearly polarized output with a tuning range of 33 nm is demonstrated in a two-chip VECSEL.

In the experiment, we use two slightly different VECSEL chips, whose gain peak wavelengths offset by $\sim$4 nm. They were used in previous two-chip VECSEL coherent power-scaling experiment and the details of their structures and sample processing were described in [5]. A W-shaped cavity as illustrated in Fig. 1 is designed for this tunable two-chip VECSEL. In the cavity, the highly reflecting (HR) concaved spherical folding mirror has a radius of curvature (ROC) of 30 cm, and full folding angle is approximately 15°. The distance between the concaved mirror and the VECSEL Chips 1 and 2 are around 24 and 21 cm, respectively. The flat output coupler is 4.5 cm away from the VECSEL Chip 1, and the HR flat mirror is

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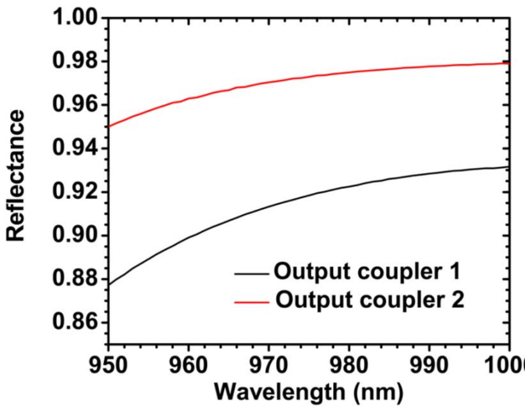

Fig. 2. Reflectance spectra of output couplers in the tuning range of the laser.

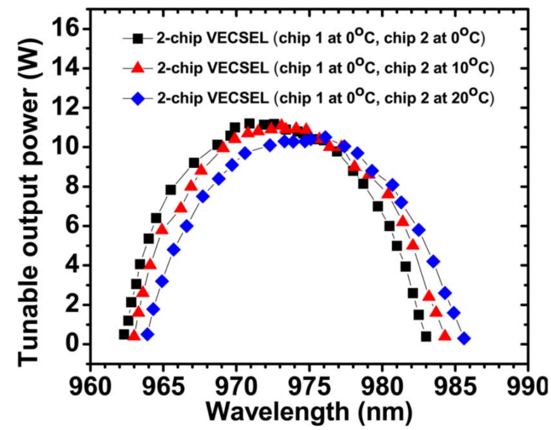

Fig. 3. Tuning curve of the two-chip VECSEL with Output Coupler 1.

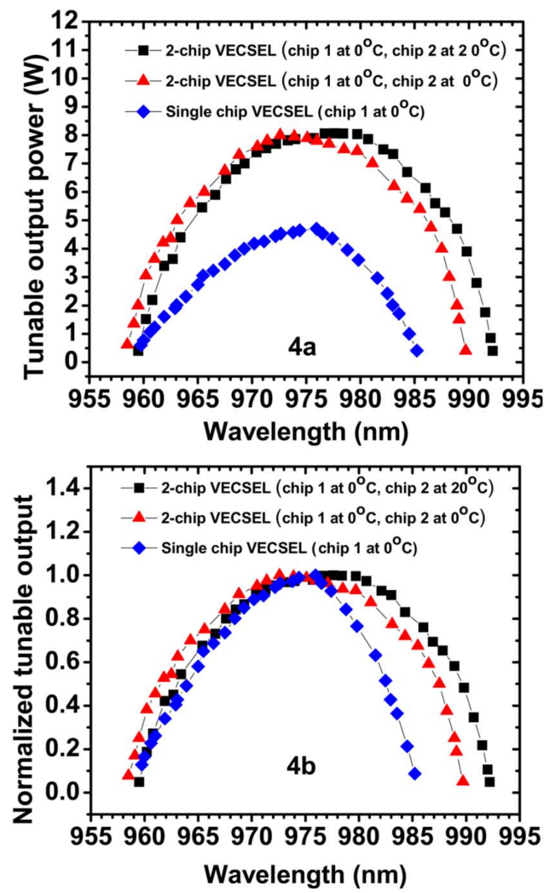

Fig. 4. Tuning curve of the two-chip VECSEL with Output Coupler 2, and the comparison of tuning properties between a single-chip and two-chip VECSEL.

7 cm from the Chip 2. A 2-mm-thick quartz plate is inserted between the flat HR mirror and Chip 2 at Brewster's angle serving as a BF. This BF is an extremely low loss at the tuned wavelength, and introduces the longitudinal mode discrimination to narrow the lasing spectra [1]. This cavity configuration defines TEM_{00} mode size on VECSEL Chip 1: $\sim$350-μm diameter (tangential) and $\sim$360-μm diameter (sagittal); on VECSEL Chip 2: $\sim$420-μm diameter (tangential and sagittal). Two 808-nm fiber coupled pump lasers are focused on Chips 1 and 2 with a pump spot size of 410 (in diameter) and 480 μm (in diameter), respectively. Both pump spot sizes match the fundamental mode sizes on the chips to force laser operating in TEM_{00} mode. The concaved spherical mirror results in difference between the tangential and sagittal focal lengths, making the laser beam asymmetric (elliptical). Fortunately BF compensates this asymmetry (or astigmatism) somewhat [5]. To decrease this asymmetry, the folding angle at the concaved spherical mirror must be kept as small as possible. To take advantage of resonant periodic gain, the folding angle on both chips should be kept as small as possible.

When measuring the tuning curves, we tried to keep the identical pump density on both chips (19.5-W pump power was launched into Chip 1 in 410-μm diameter pump spot, and 26.5-W pump power into Chip 2 in 480-μm diameter pump spot). During the measurement, the temperature in both chips was controlled by heatsink (hereinafter, all of temperatures refer to the temperature of the heatsink), and two output couplers with different reflectance spectra, illustrated in Fig. 2, were used. Between 950 and 1000 nm, the reflectance of Output Couplers 1 and 2 is not constant, but with a few percent drop on the shorter wavelength side, so the tuning range of the laser will be reduced somewhat on the same side. VECSEL Chips 1 and 2 were characterized in the linear cavity, formed by a VECSEL chip and output coupler mirror. At the laser threshold and 0 °C, VECSEL Chips 1 and 2 lase at around 964 and 968 nm, respectively [5]. Since the VECSEL lases at the modal gain peak wavelength, the lasing wavelengths of Chips 1 and 2 reflect that their modal gain peak wavelengths offset by $\sim$4 nm.

Fig. 3 shows the laser tuning performance when Output Coupler 1 (91%–92% reflectance in the tuning range) is used. In the measurement, the temperature of the heatsink for Chip 1 is 0 °C while the heatsink for Chip 2 is at 0 °C, 10 °C, and 20 °C, respectively. Over 11-W peak output power and 21-nm wavelength tuning range are achieved. The results indicate that when the temperature on Chip 2 increases, the tuning curve and peak wavelength globally shift to longer wavelength and the peak power slightly decreases. This is due to the red-shift of the quantum-well gain and gain peak drop with the increase of the temperature.

Fig. 4(a) shows the laser tuning performance when Output Coupler 2 (96%–97.5% reflectance in the tuning range) is used. Using an output coupler with higher reflectance, we decrease the cavity losses, resulting in a larger tunability; however, the output power is sacrificed. Under the similar experimental conditions

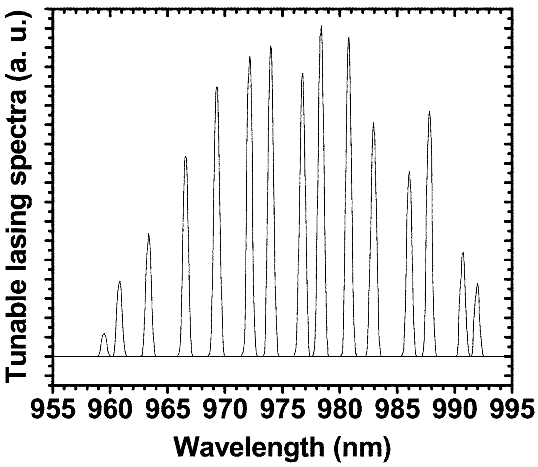

Fig. 5. Some tuning spectra within 33-nm tuning range.

(the heatsink for Chip 1 is at 0 °C, and the heatsink for Chip 2 at 0 °C and 20 °C, respectively). Over 8-W peak output power and 33-nm wavelength tuning range are achieved. Larger tunability would have been achieved if the reflectance of Output Coupler 2 had not dropped on the shorter wavelength side (see Fig. 2). With the increase of the temperature on Chip 2, the tunability slightly increases and the tuning curve globally red-shifts.

The tuning properties of this two-chip VECSEL and a single-chip VECSEL are compared under the same operation condition. The tunable single-chip VECSEL with a V-shaped cavity folded at the VECSEL chip, as described in detail in [1], was built by Chip 1, output coupler (with 30-cm ROC and same reflectance spectrum as Output Coupler 2) and the same BF and HR flat mirror used in the two-chip VECSEL. During the measurement, the Chip 1 was on the heatsink with temperature of 0 °C, and was pumped at the same pump density (25.6 W on 480-μm diameter pump spot). The cavity is optimized for TEM_{00} mode operation. The measured tuning curve of this single-chip VECSEL added in Fig. 4(a) show a 25-nm tuning range and 4.7-W peak output power. To make the comparison simpler, we normalize each tuning curve in Fig. 4(a) to its own peak power. Fig. 4(b) show their normalized tuning curves. The full-width at half-maximum of the tuning curve, used to judge tunable output power variation with the tuned wavelength, is about 18 nm for the single-chip VECSEL and 27 nm for the two-chip VECSEL. Obviously, the two-chip VECSEL extends the tunability of the laser and significantly reduces its tunable output power variation with the tuned wavelength.

The tuning spectra are measured by an optical spectral analyzer (OSA). In the measurement, the laser beam leaking from HR mirror is coupled into a multimode fiber which is connected to the OSA. Fig. 5 shows some tuning spectra along the tuning range. The variation of the strength of spectra is due to fiber coupling, not the intensity of the output beam. The linewidth is less than 1 nm. The beam quality is measured by a real-time beam profiler BeamMap (DataRay Inc.). Since pump size matches the fundamental mode size, the beam quality factor (M^2 factor) is close to 1.7 at peak output power.

It is known that the quantum-well gain peak shifts to longer wavelengths with temperature increase at a rate of 0.3–0.4 nm/K for a given carrier density [7]. Cooling Chip 1 and heating Chip 2 increases the detuning (offset) between the modal gain peaks, and may broaden the modal gain spectra of the two-chip VECSEL to increase the tunability of the laser. However, since quantum-well gain is also sensitive to temperature, tuning the gain peaks by increasing temperature has a tradeoff, that is, dropping the gain due to heating on Chip 2, thus reducing the tunability of the laser. In the experiment, raising the temperature on Chip 2 just slightly increases the tunability of the two-chip VECSEL (see Fig. 4). In practice, instead of tuning the gain peaks by temperature, employing two different chips with a somewhat large detuning (offset) between their modal gain peaks is a simple and efficient way to achieve the extended tunabililty.

In summary, we report on the development and demonstration of a multiwatt high-brightness linearly polarized tunable two-chip VECSEL with a W-shaped cavity and a BF. Multiwatts high-brightness linearly polarized output with a tuning range of 33 nm is demonstrated. The modal gain spectra of a two-chip VECSEL are the superposition of two gain spectra from different VECSEL chip, making the gain spectra higher and broader. This configuration yields a flexibility to shape the gain spectra of the laser by using two different chips with certain gain peak detuning (offset), thus, to manipulate the tuning curve of the laser. The two-chip VECSEL shows less tunable output power variation with the tuned wavelength and larger tunability than a single-chip VECSEL does. In addition, the broad bandwidth of two-chip gain is of great importance for the generation of ultrashort pulses in the mode-locked VECSEL.

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